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14. ABSTRACT
Over the course of the project we have completed the liquid state NMR implementation of the QIP test-bed and are now using it to explore a variety of efficient error finding protocols. This setup has enabled us to extend the coherent control methods to superconducting flux qubits, electron/nuclear spin systems and to neutron interferometry. In all of these the focus is to control decoherence and to experimentally investigate noise sources of decoherence.

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Quantum Information Processors and Test-Beds

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QCCM - Center for NMR Quantum Information Processing

ABSTRACT

Over the course of the project we have completed the liquid state NMR implementation of the QIP test-bed and are now using it to explore a variety of efficient error finding protocols. This setup has enabled us to extend the coherent control methods to superconducting flux qubits, electron/nuclear spin systems and to neutron interferometry. In all of these the focus is to control decoherence and to experimentally investigate noise sources of decoherence.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. Experimental realization of electromagnetically induced transparency in liquid-state NMR.
L E. Fernandes, J. T. Choy, D. R. Khanal and D. G. Cory.
Concepts in Magnetic Resonance Part A, 30A(5), 236-245, 2007.

2. Symmetrized characterization of noisy quantum processes.
J. V. Emerson, M. Silva, O. Moussa, C. Ryan, M. Laforest, J. D. Baugh, D. G Cory and R. Laflamme
Science, 317(5846), 1893-1896, 2007.

3. Using error correction to determine the noise mode
M. Laforest, D. Simon, J.-C. Boileau, J. Baugh, M. Ditty, and R. Laflamme
Physical Reviews A 75, 012331, 2007

4. Quantum Information Processing Using NMR and EPR: Review and Prospects
J. Baugh, J. Chamilliard, M. Ditty, A. Hubbard, M. Laforest, C. Madaiah, O. Moussa, C. Negrevergne, M. Silva, S. Simmons, C. A. Ryan, R. Laflamme, J. S. Hodges, C. Ramanathan, and D. G. Cory
Physics in Canada, 2008, 86, 557-561

5. Measurements of the vertical coherence length in neutron interferometry
D. A. Pushin, M. Arif, M. G. Huber, and D. G. Cory
Physical Review Letters, 100(25), 250404, 2008

6. Dynamic nuclear polarization in silicon microparticles.
A. E. Dementyev, D. G. Cory and C. Ramanathan
Physical Review B, 77(2), 024413, 2008

7. Rapid diffusion of dipolar order enhances dynamic nuclear polarization
A. E. Dementyev, D. G. Cory and C. Ramanathan
Physical Review B, 2008, 77, 010802, 1 – 6.

8. Universal control of nuclear spins via anisotropic hyperfine interactions
J. S. Hodges, J. C. Yang, C. Ramanthan and D. G. Cory
Physical Review A, 78(1), 010303, 2008

9. Symmetrization methods for characterization and benchmarking of quantum processes
J. Emerson
Canadian Journal of Physics, 86, 557-561, 2008

10. A spin based heat engine: demonstration of multiple rounds of algorithmic cooling
C. A. Ryan, O. Moussa, J. Baugh, R. Laflamme
Physical Review Letters, 100, 140401, 2005

11. Control of Qubits Encoded in Decoherence-Free Subspaces
P. Cappellaro, J. S. Hodges, T. F. Havel, and David Cory
Laser Physics, 17, 545-551, 2007

12. Fidelity Enhancement by Logical Qubit Encoding
M. Henry, C. Ramanthan, J. Hodges, C. Ryan, M. Ditty, R. Laflamme, and D. G. Cory
Physical Review Letters, 99, 220501, 2007

13. Measurements of the Vertical Coherence Length in Neutron Interferometry
D. A. Pushin, M. Arif, M. G. Huber, and D. G. Cory
Physical Review Letters, 100, 250404, 2008

14. Error Characterization in Quantum Information Processing: A Protocol for Analyzing Spatial Correlations and its Experimental Implementation
Cecilia C. Lopez, Bejamin Levi, and David G. Cory

Physical Review A, 79, 042328, 2009

15. Signal Optimization in Inhomogeneous Fields: Application of Quantum Optimal Control Theory
T. W. Bordeman, D. G. Cory, and M. D. Hurlimann
Diffusion Fundamentals, 10, 12.1-12.3, 2009

16. NMR multiple quantum coherences in quasi-one-dimensional spin systems: Comparison with ideal spin-chain dynamics
W. Zhang, P. Cappellaro, N. Antler, B. Pepper, D. G. Cory, V. Dobrovitski, C. Ramanathan, and L. Viola
Physical Review A, 80, 052323, 2009

17. Decoherence-free Nuetron Interferometry
D. A. Pushin, M. Arif, and D. G. Cory
Physical Review A, 79, 05636, 2009

18. Testing Contextuality on Quantum Ensembles with One Clean Qubit
O. Moussa, C. A. Ryan, D. G. Cory and R. Laflamme
Physical Review Letters, 104, 160501, 2010

19. Repetitive Readout of Single Electron Spin via Quantum Logic with Nuclear Spin Ancillae
L. Jiang, J. S. Hodges, J. R. Maze, P. Maurer, J. M. Taylor, D. G. Cory, P. R. Hemmer, R. L. Walsworth, A. Yacoby, A. S. Zibrox, and M. D. Lukin
Science, 326, 267-272, 2009

20. Progress Toward Scalable Tomography of Quantum Maps Using Twirling-Bases Methods and Information Hierarchies
C. C Lopez, A. Bendersky, J. P. Paz, and D. G. Cory
Physical Review A, 81, 062113, 2010

21. Robust decoupling techniques to extend quantum coherence in diamond
C. A. Ryan, J. S. Hodges, and D. G. Cory
Physical Review Letters, 2010, 105, 200402

22. Application of Optimal Control of CPMG Refocusing Pulse Design
T. W. Borneman, M. D. Hurlimann, and D. G. Cory
Journal of Magnetic Resonance, 2010, 27, 220-233

Number of Papers published in peer-reviewed journals: 22.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

1. Dynamic nuclear polarization and spin diffusion in nonconducting solids
C. Ramanathan
Applied Magnetic Resonance

2. Dynamic nuclear polarization in intermediately-Doped Single Crystal Silicon
A. Dementyev, D. G. Cory, C. Ramanathan
Journal of Chemical Physics

3. Using an experimentally faulty Quantum Information Process to characterize its own performance
Cecilia C. Lopez, Marcus Silva, Joseph Emerson and D. G. Cory
Physical Review A

4. Realization of Decoherence-Free Nuetron Interferometry
D. A. Pushin, M. G. Huber, M. Arif, and D. G. Cory
Physical Review A

5. Dynamical Decoupling and Noise Spectroscopy with a Superconducting Flux Qubit,
J. Bylander, S. Gustavsson, F. Yan, F. Yoshihara, K. Harrabi, G. Fitch, D. G. Cory, Y. Nakamura, J.-S. Tsai, and W. D. Oliver
Nature

Number of Manuscripts: 5.00

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
Troy Borneman	0.81
Jonathan Hodges	0.08
Cecilia Lopez	0.75
Chonlagarn Iamsumang	0.03
Jamie Yang	0.01
FTE Equivalent:	**1.68**
Total Number:	**5**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
Brian Pepper	
Natania Antler	0.00
FTE Equivalent:	**0.00**
Total Number:	**2**

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 2.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 2.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 2.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Jamie Yang	
Jonathan Hodges	
Total Number:	**2**

Names of personnel receiving PHDs

NAME	
Jamie Yang	
Jonathan Hodges	
Cecilia Lopez	
Colm Ryan	
Osama Moussa	
Total Number:	**5**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Several multi-pulse sequences developed within the field of nuclear magnetic resonance (NMR) have recently been applied to mitigate noise in qubits based on atomic ensembles, semi-conductor quantum dots, and diamond nitrogen-vacancy centers. We extend these methods to the realm of superconducting quantum devices, and subject a remarkably long-lived qubit to varying levels of longitudinal and transverse noise by rotating the qubit's quantization axis, against which we characterize the baseline coherence rates Γ_1, Γ_2, and Γ_φ. We evaluate three dynamical decoupling pulse protocols: the Carr-Purcell (CP); Carr-Purcell-Meiboom-Gill (CPMG); and Uhrig dynamical decoupling (UDD) sequences. The narrow-band filtering property of the CPMG sequence enables us to sample environmental noise over a broad frequency range 0.2-20MHz, and we observe a $1/f^\alpha$-type spectrum which we independently confirm with a Rabi-spectroscopy approach. We further characterize the environmental noise from 5.4 to 21 GHz, by monitoring the qubit's relaxation rate.

The device is a persistent-current qubit, an aluminium loop interrupted by four A1-A1O$_x$-A1 Josephson junctions. When an external magnetic flux Φ threading the loop is close to half a superconducting flux quantum $\Phi_0/2$, the diabatic states correspond to clockwise (counterclockwise) persistent currents, $I_p = 0.18\mu$A with energies $\pm\hbar\varepsilon/2 = \pm I_p\Phi_b$, tunable by the flux bias $\Phi_b = \Phi - \Phi_0/2$. At $\Phi_b = 0$, the degenerate persistent-current states hybridize with a strength $\hbar\delta = h \times 5.3662$ GHz, where $\hbar = h/2\pi$ and h is Planck's constant. The corresponding two-level Hamiltonian is

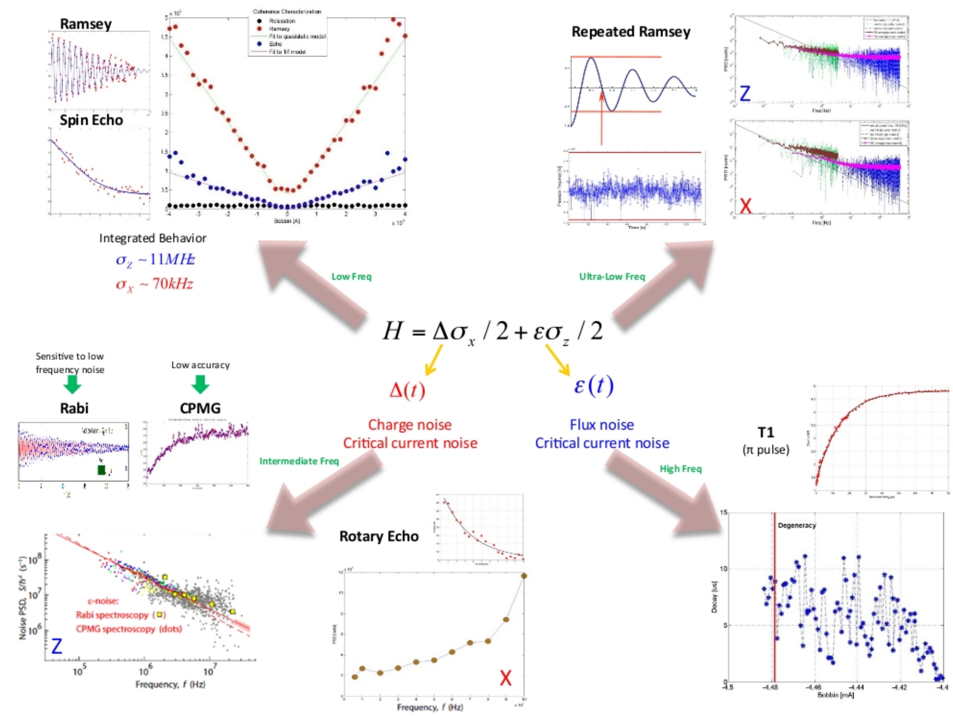
$$\hat{\mathcal{H}} = -\frac{\hbar}{2}\left[(\varepsilon + \delta\varepsilon)\hat{\sigma}_x + (\Delta + \delta\Delta)\hat{\sigma}_x\right], \quad (1)$$

which includes noise fluctuation terms $\delta\varepsilon$ and $\delta\Delta$ and $\hat{\sigma}_{x,z}$ are Pauli operators. The ground ($|0\rangle$) and excited ($|1\rangle$) states have frequency splitting $\omega_{01} = \sqrt{\varepsilon^2 + \Delta^2}$ and are well isolated owing to the qubit's large anharmonicity, $\omega_{12}/\omega_{01} \approx 5$. The environmental noise leading to fluctuations $\delta\varepsilon$ (*e.g.*, flux noise) and $\delta\Delta$ (*e.g.*, critical current and charge noise) physically couples to the qubit in the $\varepsilon - \Delta$ frame. However, their manifestation as longitudinal noise (dephasing) or transverse noise (energy relaxation) is tunable by the flux bias Φ_b and determined, respectively, by their projections $\delta\omega_{z'}$ onto the qubit's quantization axis $\hat{\sigma}_{z'}$ (which makes an angle $\theta = \arctan(\varepsilon/\Delta)$ with $\hat{\sigma}_z$) and $\delta\omega_{\perp'}$ onto the plane perpendicular to $\hat{\sigma}_{z'}$.

Table 1: **Quasi-static noise parameters used in simulations, and coherence times.**

Noise parameters	$\sigma_\lambda/2\pi$	ω_{ir}^λ	$\omega_{uv}^\lambda/2\pi$	A_λ
$\lambda = \varepsilon$ (equiv. Φ noise)	10MHz	1Hz	1MHz	$(1.7 \times 10^{-6})^2\Phi_0^2$
$\lambda = \Delta$ (equiv. I/I_c noise)	0.06MHz	1Hz	¡0.1MHz	$(4.0 \times 10^{-6})^2$
Coherence times	T_1	T_1^*	T_2^{CPMG}	$T_2^{\mathrm{CPMG}}/T_2^*$
$\Phi_b = 0\mathrm{m}\Phi_0$	12μs	2.5μs	23μs$(N=1)$	9
$\Phi_b = 0.4\mathrm{m}\Phi_0$	12μs	0.27μs	12μs$(N=200)$	48

In Ramsey-fringe and Hahn-echo simulations, we describe the Gaussian noise distributions by their standard deviations, σ_λ, obtained by integrating the $1/f$ noises over the bandwidth given by the experimental protocol (cut-off frequencies ω_{ir}^λ and ω_{uv}^ε). At $\varepsilon = 0$, the dephasing improvement under a Hahn echo is greater than the theory would suggest for $\delta\Delta 1/f$ noise that extends to high frequencies; the lower ω_{uv}^Δ gives consistency. The equivalent flux and normalized critical-current noise amplitudes, A_λ, are values derived from the Ramsey and echo data assuming a power law $1/f^\alpha$ with $\alpha = 1$ and that all noise in ε and Δ is flux and critical-current noise, respectively; they are consistent with previously reported values. Using these parameters in simulations yielded agreement with N-pulse dynamical decoupling data, consistent with equation. The coherence times are given two bias points dominated by $\delta\Delta$ and $\delta\varepsilon$ noise, respectively.



We experimentally demonstrate over two orders of magnitude increase in the coherence time of nitrogen vacancy centres in diamond by implementing decoupling techniques. We show that for the relevant noise model, conventional magnetic resonance decoupling techniques with equal pulse spacings, out-perform, or perform no worse than, those with variable pulse spacings. At short times, we can extend the coherence time of particular states out from $T_2^* = 2.7\mu s$ out to an effective $T_2 > 340\mu s$. For preserving arbitrary states we show the experimental importance of using pulse sequences that through judicious choice of the phase of the pulses compensate the imperfections of individual pulses for all input states. At longer times, we can arrange revivals in the coherence for all input states at particular times and we use compensated sequences to enhance these revivals and show a coherence time of over 1.6ms in ultra-pure abundance ^{13}C diamond.

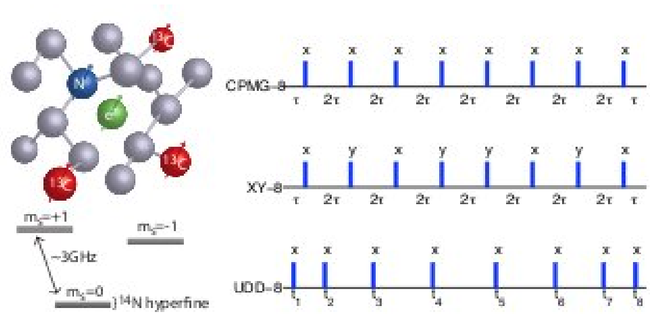


FIG. 1: (a) NV in diamond lattice with the electron spin (green) coupled to the surrounding nuclear spins $^{14/15}N$ (blue) at the defect and ^{13}C (red) in the lattice. The electron ground state level structure is shown below. (b) An example with eight pulses of the three decoupling sequences used: CPMG; XY-8 and UDD. CMPG and XY have the same pulse spacings by the phases of the XY-8 pulses are alternated. The timing of the center of the k^{th} UDD pulses with N total pulses is given by $\sin^2(\pi k/(2N+2))$.

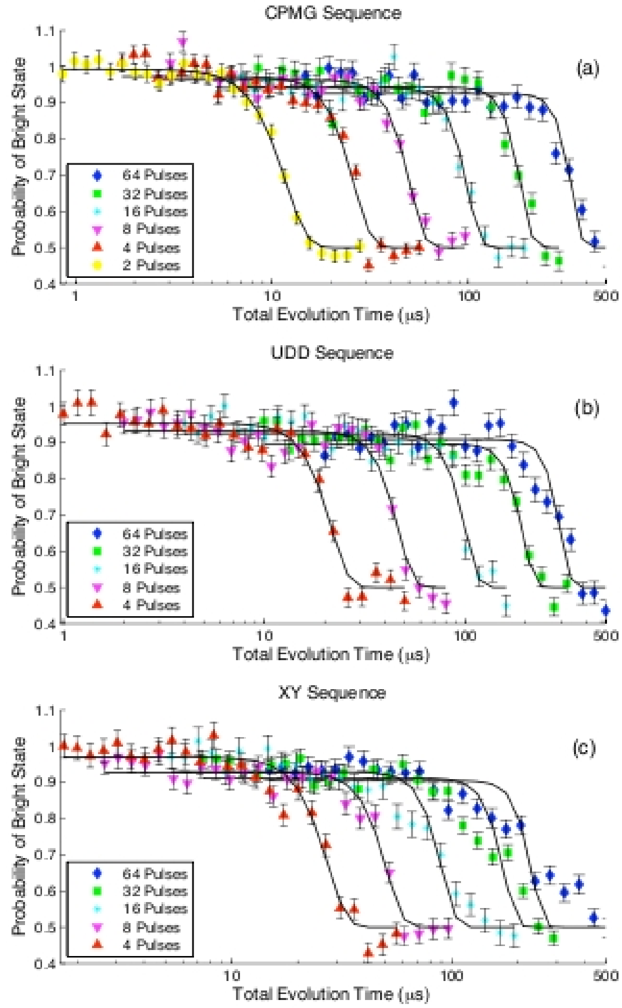


FIG. 2: Short-time coherence decay for states along the pulse rotation axis with (a) CPMG, (b) UDD and (c) XY sequences. Fits are to the phenomenological form $s(t) = 0.5 + A\exp(-(\frac{t}{T_2})^k)$ where $k = \log_2(\text{number of pulses}){+}3$. Error bars are propagated from photon counting statistics.

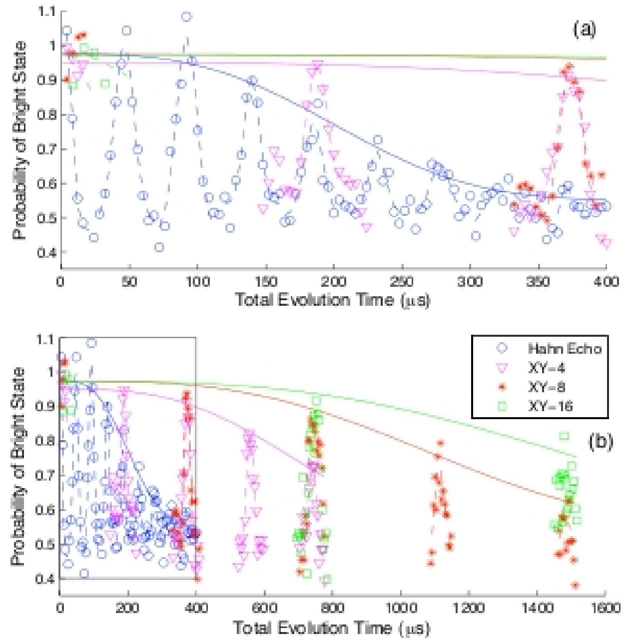


FIG. 3: The effect the robust XY multiple pulse sequences on the revivals at short times (a) and longer times (b). At short times the periodic revivals of the single spin echo are observed to decay with at $220\mu s T_2$ With multiple pulses the revival frequency is reduced proportionally but the T_2 is greatly extended to over 1.6 ms. The envelopes are fit to $(s(T) = 0.5 + A\exp(-(\frac{t}{T_2})^3)$. Since the revivals only occur at certain multiples of the bare ^{13}C frequency, we observe only at these times to reduce experimental time.